Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Detecting and Quantifying Damage in Buildings using Earthquake Response Data and Capacity Curves

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ABSTRACT: The focus of this research is developing the ability to detect and quantify damage in buildings following earthquakes. In particular, the hysteretic behavior of a subject building that has been subject to earthquake ground motion is estimated using the recorded acceleration response and derived velocity and displacement responses of the building. The hypothesis is that building acceleration records contain sufficient characteristic information to develop the lateral-load resistance curve, also known as the capacity curve, of the building to the extent the building was forced to during an earthquake. This research allows comparing standard practice prediction methods, such as computer generated pushover curves, with partial capacity curves generated from measured earthquake response acceleration data.

1 INTRODUCTION AND BACKGROUND

Strong ground motions can damage buildings and infrastructure. In seismic design, structural engineers design buildings with the intent of preventing collapse while expecting inelastic behavior to occur in extreme strong ground motion events. In design, structural engineers rely on idealized mathematical models of the structural systems and nonlinear analysis methods to estimate the capacity of a building to resist the demand of strong earthquake ground motions. Typically this capacity is expressed in terms of roof displacement versus base shear force, a relationship also known as the building capacity curve. Compared to estimates and approximations based on numerical nonlinear analyses, a capacity curve constructed from actual building response data would be a more realistic representation of the behavior of the building.

Gilmartin et al. (1998) and Freeman et al. (1999) describe a method for generating a capacity curve using building response data recorded during strong ground shaking. The method requires roof acceleration response data and ground acceleration data. The roof relative displacement is used to estimate the fundamental period of the structure using the duration between consecutive peak displacement response instants. The estimated fundamental mode relative roof displacement, obtained by averaging the consecutive peak fundamental mode displacement responses, and estimated fundamental period can be used to approximate the fundamental mode roof acceleration response and ultimately the fundamental mode capacity curve. While the method does not require special software or complicated signal processing techniques, it requires engineering judgment which prohibits automating the process to determine the nature of the structural response rapidly after strong ground shaking.

In lieu of the simple procedure developed by Freeman et al. (1999), researchers have used Fourier-based methods to estimate the change in the fundamental period of a building from earthquake response data (Bradford et al., 2006, Moaveni et al., 2012, Zhang et al., 2005). Fourier-based methods assume the signal is linear and stationary which is not the case for strong ground motion building response data. Nonlinearity in building response usually occurs in the few seconds when the ground motion is strongest, so complications in balancing the time and frequency resolution arise when using windowed response data.

The Hilbert-Huang transform, a combined use of the empirical mode decomposition and Hilbert transform, was developed by Huang et al. (1998) to produce the instantaneous frequency over time for nonlinear and non-stationary data. Loh et al. (2001) uses the Hilbert-Huang transform to detect the period of a building from the nearly linear response from weak ground motions and during the free vibration of the building immediately after a strong ground motion. A drawback to the Hilbert-Huang transform is the contamination of the instantaneous frequency output by the ground excitation frequency. Luna (2009) and Tanikella (2012) each proposed using the empirical mode decomposition to extract the fundamental response of the building. By tracking the period by looking at the duration between response peaks, period elongation or stiffness degradation could be tracked from the response.

Each of methods, whether Freeman et al. (1999), Fourier-based methods, or Hilbert-Huang transform, requires tracking the fundamental period of the building to generate a capacity curve for the fundamental response. Depending on the event, the methods may require the entire duration of the response to generate a single capacity curve. If an output-only analysis is made, that is, one that uses roof acceleration record only, errors in the results occur due to mixing of the ground motion frequencies with the building characteristic frequencies.

2 PROPOSED METHOD

As an alternative to using the building response period to generate a capacity curve for a building, a restoring force, or story shear, based method is presented to generate a capacity curve from the strong motion response data of a building. By using a restoring force based method, errors associated with the input frequency mixing with the system frequency are avoided, and a capacity curve can be generated using multiple hysteresis loops.

2.1 Single Degree of Freedom Building

For a single-degree of freedom building with assumed equivalent viscous damping and accelerometers on the roof and ground, a story capacity curve can be estimated using inter-story hysteresis loops. The inter-story hysteresis loops are composed of the mass normalized restoring force and the inter-story drift. The mass normalized restoring force is equal to the mass normalized equivalent viscous damping force subtracted from the response acceleration. The equivalent viscous damping force is found by using a damping correction procedure which is explained below. The inter-story drift is found by numerically integrating the response acceleration and using zero-phase frequency base filters. The filtering process removes the low-frequency components but preserves the phase of the signal.

The damping correction procedure assumes the damping force is linearly proportional to the relative velocity of the building, and for simplicity, the building is assumed to have rigid floor and flexible columns. The procedure is based on the fact that a peak in the restoring force occurs at the instance of a zero relative velocity. The mass normalized restoring force is estimated empirically by adding damping constant, C_{d1} multiplied by the negative relative velocity and the negative absolute acceleration response. This damping constant is the mass normalized damping coefficient. A range of values, chosen by the engineer, are used to find the damping constant C_{d1} that causes a peak in the estimated mass normalized restoring force to occur at the same instant of a zero relative velocity. Each zero relative velocity-peak mass normalized restoring force instance in the response will have a separate damping constant, C_{d1}. The estimated damping constants can be averaged for the duration of response of interest to obtain a single equivalent viscous damping constant or could be modeled as time-varying depending on the degree of variance of the damping constant estimated at different peaks.

With the mass normalized story restoring force and inter-story drift, inter-story force-displacement hysteresis loops can be generated. These inter-story capacity curves could be used to detect stiffness degradation, strength degradation, or find confidence intervals for the estimated inter-story capacity curve.

2.2 Multi-degree of Freedom Building

For a multi-degree of freedom building with accelerometers at each floor for a given response direction, a procedure similar to the single-degree of freedom buildings can be used to generate inter-story hysteresis loops and inter-story capacity curves. The multi-degree of freedom building is assumed to be a discrete mass system with mass concentrated at each floor, and have rigid floors and flexible columns.

The inter-story hysteresis loops require using inter-story coordinates for the drift at each story. Zero-phase frequency-based filters can be used to correct the acceleration response at each floor, and the difference between derived floor displacements will be the inter-story drift. The inter-story mass normalized restoring force is equal to the mass normalized inter-story viscous damping force subtracted from the mass normalized inter-story inertial force. The inter-story inertial force is equal to the sum of the acceleration responses of the floors above the story being analyzed. However, if the mass of an upper floor is different from the mass of the current floor supported by the story being analyzed, contribution of the inertial force of that floor to the mass normalized story inertial force needs to be scaled by the ratio of the mass of that floor and the mass of the current floor.

A damping correction procedure, similar to the one used for the single-degree of freedom building, is used to obtain the mass-normalized story restoring force. The damping force is assumed to be linearly proportional to the inter-story velocity. For different peaks in the mass normalized inter-story inertial force, a damping constant, C_{dn}, can be found that causes a peak in the mass normalized inter-story restoring force to occur at the same time as a zero in the inter-story velocity.

An inter-story capacity curve can be generated for each story using the inter-story hysteresis curves. These inter-story capacity curves could be used to detect stiffness degradation, strength degradation, or find confidence intervals for the estimated inter-story capacity curve. This procedure can detect damage at a story resolution for multi-degree of freedom buildings with accelerometers at each floor.

3 COMPUTER SIMULATIONS

3.1 Single Degree of Freedom Building

A single-degree of freedom building with Bouc-Wen hysteresis and 5% equivalent viscous damping is excited at the base with the ground motion recording from the 1995 Kobe earthquake at the Takatori recording station, shown in Figure 1. The model stiffness decreases proportional to the absorbed hysteretic energy. Figure 2 shows the acceleration response and numerically integrated and filtered relative velocity and drift of the roof for 2 to 12 seconds during the strongest ground excitation. In the drift, the filtering removes the low frequency component of the signal. Therefore, permanent deformation information is lost.

The damping coefficient is estimated using the procedure explained in Section 2.1. A damping coefficient is estimated for each response peak. Figure 3 shows a plot of the estimated damping coefficients at different instants, i.e. when the response has peaks. An average of the estimated damping coefficients estimates 5.2% equivalent viscous damping.

The mass normalized hysteresis cycles are shown in Figure 4. The estimated hysteresis cycles differ from the actual hysteresis cycles when comparing the displacement at zero restoring force locations. This phenomenon is due to loss of permanent drift information in the estimated hysteresis cycles. The slope of the response decreases over time in the hysteresis cycles. Figure 5 shows the instantaneous stiffness of the building when the restoring force is zero for both the actual case (model) and estimated case (estimated from simulation results).

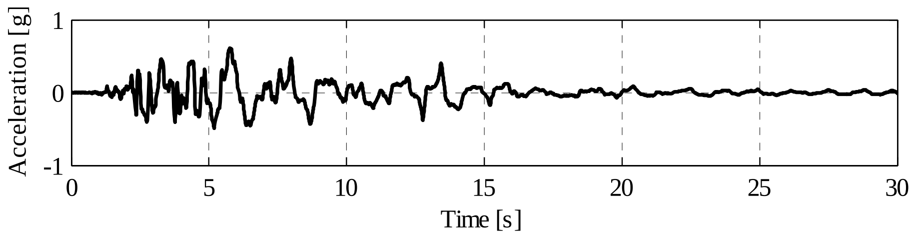

Figure 1: 1995 Kobe ground motion recorded at the Takatori station

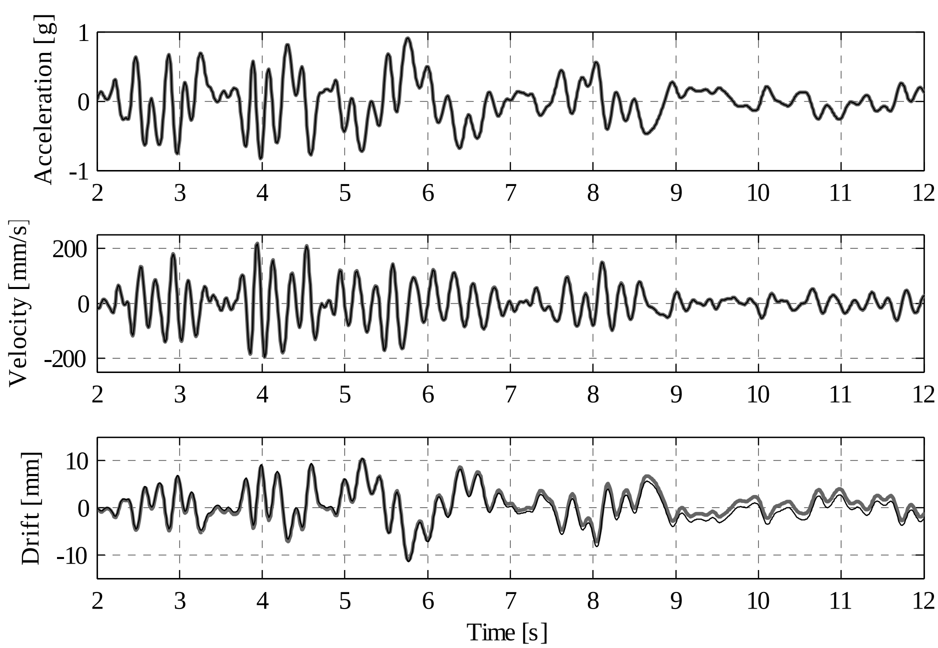

Figure 2: Bouc-Wen model 1st story response: actual response (grey), estimated (black)

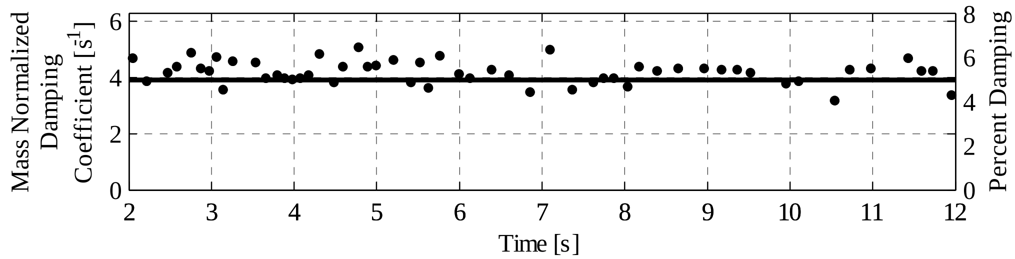

Figure 3: Damping coefficient estimation: estimated damping coefficient (black dot), 5% viscous damping (solid black line)

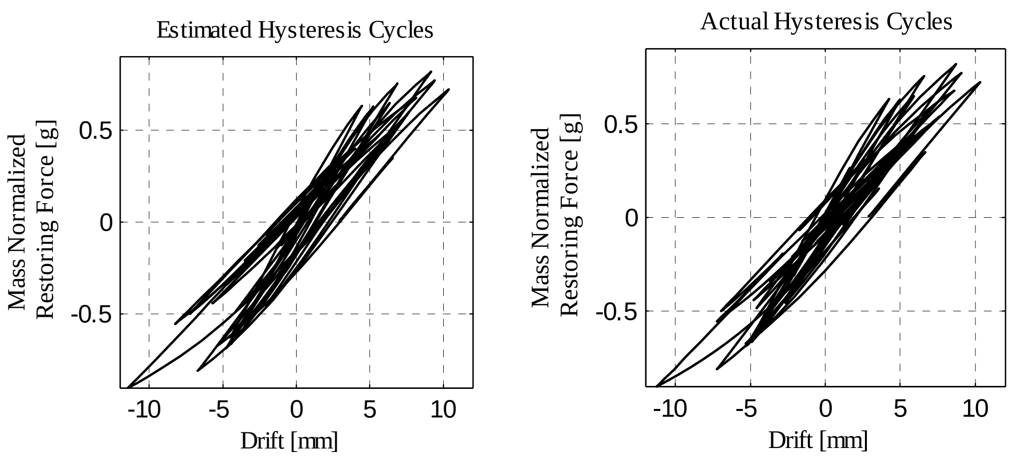

Figure 4: Actual and estimated hysteresis cycles between 2 and 12 seconds

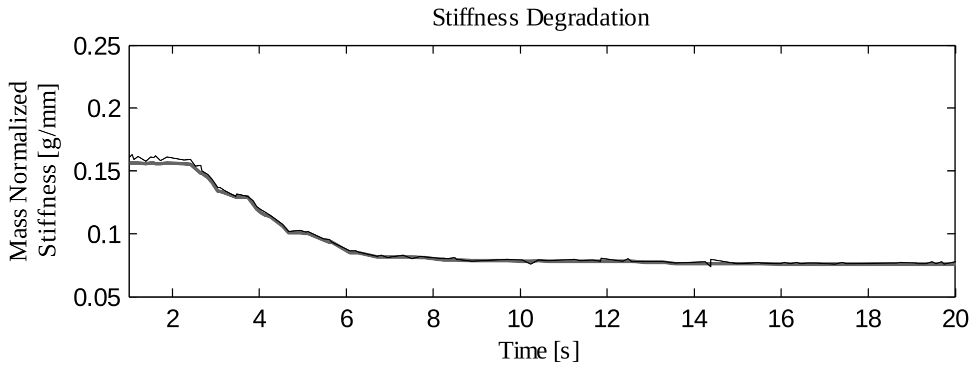

Figure 5: Stiffness degradation: actual stiffness at zero crossing (grey line), estimated stiffness at zero crossing (black line)

3.2 Five Degree of Freedom Building

A five-degrees of freedom building with rigid floors and flexible columns, with bilinear inter-story hysteresis and 5% stiffness proportional viscous damping in the fundamental mode is excited with the ground motion shown in Figure 1. Using the procedure explained in Section 2.2, inter-story hysteresis cycles can be generated if the acceleration response is known at all floors, including the ground. Figure 6 shows the estimated and actual hysteresis cycles at the first story of the five-degrees of freedom building simulation.

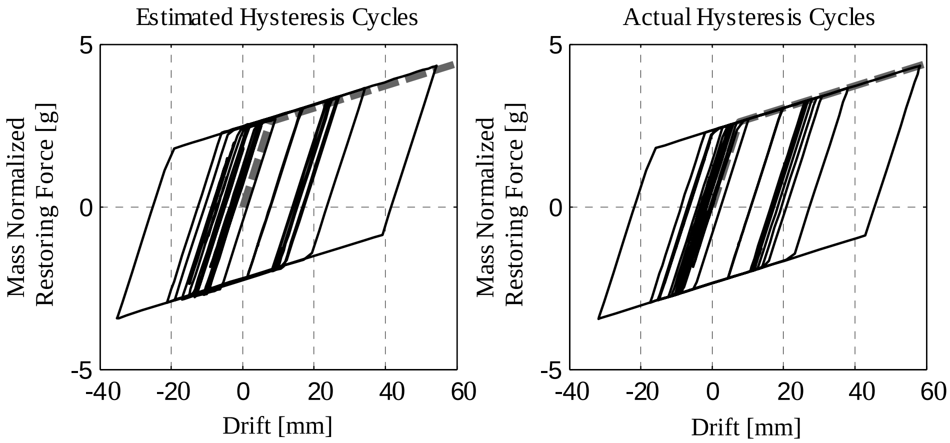

Figure 6: First story inter-story hysteresis loops (black lines) and actual capacity curve (grey dashed line)

4 DETECTING AND QUANTIFYING DAMAGE

After a strong ground motion event, the inter-story capacity curves for a building provide valuable information regarding severity of damage and story-resolution damage location within the building. The capacity curve at different instants or cycles can show that yielding of components has begun at a certain story or over time the stiffness or strength of the system is degrading. Sudden drops in load carrying capacity at a certain floor may be an indicator of a brittle failure. The inter-story capacity curves cannot provide details of component specific damage but can provide engineers with information useful to make a decision about the structural integrity of a building following a strong ground motion such as quantifiable inter-story ductility ratios, sudden drops in load carrying capacity, and time-dependent stiffness and or strength degradation.

5 CONCLUSION

The proposed method for determining the capacity curve of a building is based on restoring force estimated from response acceleration. The damping force is assumed to be linearly proportional with the relative velocity and estimated by knowing that the peak of the restoring force must occur at the same time relative velocity is equal to zero. The method is applied to idealized computer models to demonstrate how the hysteresis curves obtained from the response data can be used to generate a capacity curve. The extent of nonlinear response and degrees of stiffness degradation, if present, can also be identified easily. The method is currently tested on small-scale specimen experimental data and will be applied to real building earthquake response data.

6 REFERENCES

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